aa501
psfig
document

H ii Hα Hβ W(Hβ) W(WR) I(WR)/I() Lyman-α He i He i λ4471 He ii He ii λ4686 q(H) q(He^0) q(He$^+$) Q(H) Q(He^0) Q(He$^+$) Q(LW) q(He^0)/q(H) q(He$^+$)/q(H) Q(He^0)/Q(H) Q(He$^+$)/Q(H) $\bar{Q}$(H) $\bar{Q}$(He^0) $\bar{Q}$(He$^+$) $\bar{Q}$(H$_2$) $\bar{Q}$(He^0)/$\bar{Q}$(H) $\bar{Q}$(He$^+$)/$\bar{Q}$(H)

Δt $12 + \log$(O/H) [N ii] [O i] [O ii] [O iii] N iii λ4512 N v λ4612 N iii λ4640 C iv λ4658 C iii λ5696 C iv λ5808

VLT observations of metal-rich extra galactic HII regions. I. Massive star populations and the upper end of the IMF Based on observations ESO/VLT service observations (65.N-0308 and 67.B-0197)

Maximilien Pindao1 Daniel Schaerer 2 Rosa M. González Delgado 3 Grażyna Stasińska 4

D. Schaerer, schaerer@ast.obs-mip.fr

Observatoire de Genève, Ch. des Maillettes 51, CH-1290 Sauverny, Switzerland Observatoire Midi-Pyrénées, Laboratoire d'Astrophysique, UMR 5572, 14, Av. E. Belin, F-31400 Toulouse, France Instituto de Astrofísica de Andalucía (CSIC), Apdo. 3004, E-18080, Granada, Spain LUTH, Observatoire de Meudon, 5, Place Jules Jansses, F-92150 Meudon, France

Received 20 june 2002/ Accepted 12 august 2002

Metal-rich regions and the IMF

We have obtained high quality FORS1/VLT optical spectra of 85 disk regions in the nearby spiral galaxies NGC 3351, NGC 3521, NGC 4254, NGC 4303, and NGC 4321. Our sample of metal-rich regions with metallicities close to solar and higher reveal the presence of Wolf-Rayet (WR) stars in 27 objects from the blue WR bump ($\sim$ 4680 Å) and 15 additional candidate WR regions. This provides for the first time a large set of metal-rich WR regions.

Introduction s$_i$$ntro$

Wolf-Rayet stars (WR) are the descendants of the most massive stars. Although they live during a short time (Maeder & Conti 1994) these stars have been detected in young stellar systems, such as extragalactic HII regions (Kunth & Schild 1986) and the so-called WR galaxies (Conti 1991, Schaerer et al. 1999b). They are recognized by the presence of broad stellar emission lines at optical wavelengths, mainly at 4680 Å (known as the blue WR bump) and at 5808 Å (red WR bump). The blue bump is a blend of N v $\lambda\lambda$4604,4620, N iii $\lambda\lambda$4634,4641, C iii/iv $\lambda\lambda$4650,4658 and lines, that are produced in WR stars of the nitrogen (WN) and carbon (WC) sequences. In contrast, the red bump is formed only by and it is mainly produced by WC stars. The detection of these features in the integrated spectrum of a stellar system provides a powerful tool to date the onset of the burst, and it constitutes the best direct measure of the upper end of the initial mass function (IMF). Thus, if WR features are found in the spectra of star forming systems, stars more massive than $M_{\rm WR}$, where $M_{\rm WR} \sim 25$ M$_\odot$ for solar metallicity, must be formed in the burst.

The IMF is one of the fundamental ingredients for studies of stellar populations, which has an important bearing on many astrophysical studies ranging from cosmology to the understanding of the local Universe. In particular the value of the IMF slope and the upper mass cut-off (M$_{\rm up}$) strongly influences the mechanical, radiative, and chemical feedback from massive stars to the ISM such as the UV light, the ionizing radiation field, and the production of heavy elements.

A picture of a universal IMF has emerged from numerous works performed in the last few years (e.g. Gilmore & Howell 1998 and references therein). Indeed, these studies derive a slope of the IMF close to the Salpeter value for a mass range between 5 and 60 M$_\odot$. This result seems to hold for a variety of objects and metallicities from very metal poor up to the solar metallicity, with the possible exception of a steeper field IMF (Massey et al. 1995, Tremonti et al. 2002). However, the IMF in high metallicity (12+log (O/H) (O/H)$_\odot \approx 8.92$) systems is much less well constrained. Different indirect methods to derive the slope and M$_{\rm up}$ give contradictory results.

The detection of strong wind resonance UV lines in the integrated spectrum of high metallicity nuclear starbursts clearly indicate the formation of massive stars (Leitherer 1998; Schaerer 2000; González Delgado 2001). In contrast, the analysis of the nebular optical and infrared lines of IR-luminous galaxies and high metallicity regions indicates a softness of the ionizing radiation field that has beeninterpreted as due to the lack of stars more massive than $\sim$ 30 M$_\odot$ (Goldader et al. 1997; Bresolin et al. 1999; Thornley et al. 2000; Coziol et al. 2001). However, the interpretation of these indirect probes relies strongly on a combination of models for stellar atmospheres and interiors, evolutionary synthesis, and photoionisation, each with several potential shortcomings/difficulties (cf. García-Vargas 1996, Schaerer 2000, Stasińska 2002). For example, recently González Delgado et al. (2002) have shown that the above conclusion could be an artifact of the failure of WR stellar atmospheres models to correctly predict the ionizing radiation field of high metallicity starbursts (see also Castellanos 2001, Castellanos et al. 2002b).

A more direct investigation of the stellar content of metal-rich nuclear starbursts has been performed by Schaerer et al. (2000, hereafter SGIT00), using the detection of WR features to constrain $\mathrm{M_{up}}$. They found that the observational data are compatible with a Salpeter IMF extending to masses $\mathrm{M_{up}}$ 40 $\mathrm{M_\odot}$. Most recently, a similar conclusion has been obtained by Bresolin & Kennicutt (2002, hereafter BK02) from observations of high-metallicity HII regions in M83, NGC 3351 and NGC 6384.

Here, we present a direct attempt to determine $\mathrm{M_{up}}$ based on the detection of WR features in metal-rich regions of a sample of spiral galaxies. To obtain statistically significant conclusions about $\mathrm{M_{up}}$ and the slope of the IMF, a large sample of regions needs to be observed. For coeval star formation with a Salpeter IMF and $\mathrm{M_{up}}$=120 $\mathrm{M_\odot}$ at metallicities above solar, $\sim$ 60 to 80 % (depending on the evolutionary scenario and age of the region) of the regions are expected to exhibit WR signatures (Meynet 1995; Schaerer & Vacca 1998, hereafter SV98). Thus, to find 40 regions with WR stars (our initial aim) a sample of at least 5-7 galaxies with 10 regions per galaxy needs to be observed. Spectra of high S/N (at least 30) in the continuum are also required to obtain an accurate measure of the WR features. For this propose, we have selected the nearby spiral galaxies NGC 3351, NGC 3521, NGC 4254, NGC 4303 and NGC4321, which have have sufficient number of disk regions of high-metallicity, as known from earlier studies.

Our observations have indeed allowed to find a large number of metal-rich WR regions. The analysis of their massive star content is the main aim of the present paper. Quite independently of the detailed modeling undertaken below, our sample combined with additional WR regions from Bresolin & Kennicutt (2002) allow us to derive a fairly robust lower limit on the upper mass cut-off of the IMF in these metal-rich environments (see Sect. s$_imf$).

The structure of the paper is as follows: The sample selection, observations and data reduction are described in Sect. s$_obs.Thepropertiesofthe$ $regionsarederivedinSect.$ $s_props.Sections_wrohdiscussesthetrendsoftheWRpopula$

Sample selection, observations and reduction s$_obs$

table*[htb] Galaxy sample tab$_samplecentertabularlllllllllGalaxyNEDtypeandactivity\alpha$ (J2000) δ (J2000) v_r distance

Selection of the HII regions Our target galaxies (see Table tab$_sample)areselectedamongnearbyspiralgalaxieswhereasuf$

Metallicities of all known regions were estimated from the published [O ii] λ3727 and [O iii] $\lambda\lambda$4959,5007 intensities using the standard R_{23} "strong line" method and various empirical calibrations. For the FORS1 multi-object spectroscopic observations described below regions with metallicities above solar (log R_{23} 0.6) were given first priority. Secondary criteria taken into account in the choice of the known regions were a large equivalent width, and bright continuum flux at $\sim$ 4650 Å as determined from inspection of the spectra. This procedure lead to a first selection of 4 to 7 regions per galaxy. Other regions with lower metallicities and/or lower equivalent widths were retained as secondary targets.

Up to 19 slitlets per exposure can be used for spectroscopy with FORS1. Our primary targets were first positioned using the R-band images (see below) and the remaining slitlets were filled whenever possible with secondary targets. If a slitlet was left without any of our selected regions, we attempted to target other regions selected from the images of Hodge & Kennicutt (1983). For each galaxy a nuclear spectrum, to be reported upon later, was also obtained.

Observations R band imaging was obtained with FORS1/VLT in april 2000, and was used to determine the positions of our targeted regions with sufficient accuracy. Subtracting a local average emission from the host galaxy the R band magnitudes of our target regions were determined; typical magnitudes of $m_R \sim$ 19–21 are found.

The spectroscopic observations of our sample of regions were carried out with FORS1/VLT in the second 2001 trimester. Table tab$_loggivesinformationsabouttheexactdatesandmeteorologicalconditionsduringtheobservations.$

table*[t] Log of the observations with meteorological conditions and exposure times for both grisms center tabularlccccc galaxy date weather seeing ["] exp. time blue [s] exp. time red [s]

The spectral range from 3600 Å to 1 μm was covered with a "blue" spectrum from 3600 to 6500 Å with grism 300V+10, and a "red" spectrum from 6000 to 10000 Å with grism 300I+11. The use of a 1 slit width allowed to get medium spectral resolution of around 6 Å in the blue and 12 Å in the red. Due to the limited slit size, a fraction of the total nebular emission of the regions may be lost. This effect is acounted for in our interpretation of the data (Sect. s$_{m}odels).UnlessWRstarsfollowsystematicallyadifferentspatialdistributionthanotherstarsres$

Exposure times for each galaxy (see Table tab$_{l}og)wereadaptedtoobtaininthecontinuumS/N\sim$ 30 in the blue, (needed for a precise measure of the WR bump) and $\sim$ 10 in the red (needed to measure the [S iii] $\lambda\lambda$9069,9532 lines). Spectrophotometric standard stars data were also acquired.

Data reduction and analysis Reduction was carried out using the IRAF and MIDAS packages. The first steps consisted in the usual bias subtraction, flatfield division, and 2D wavelength calibration. Flux calibration was done using a standard atmospheric extinction curve and spectrophotometric standard stars. Given that the spectrophotometric standards were not always obtained during the night of the observations, we estimate an absolute flux accuracy of $\sim$ 10 %. In addition, due to the optimisation for a maximum multiplex, the observations were not taken at parallactic angle, leading to a slight mismatch between the blue and red spectra. A quantitative analysis of the effetcs of differential refraction has not been undertaken here. As the main diagnostics used in the present paper lie in a limited wavelength range, and the observations have been taken at small airmass, this should represent a negligible source of uncertainty.

For each region, a background including sky emission and underlying emission from the galaxy was extracted from the slitlet sub-image. This procedure was non-trivial as this background spectrum had in most cases to be determined near the edges of the sub-image, where the wavelength calibration may slightly deviate from the one of the region. Special care has been taken for the red spectra, since the sky emission was often several times brighter than the region emission. We thus re-calibrated the background emission spectrum according to the region by comparing the position (and sometimes the intensity) of the sky emission lines. This time-consuming operation gave very satisfying results and useable spectra up to 1 μm for almost all regions. The final 1D spectra were generally extracted with a 4 wide aperture.

Line intensities and equivalent width were obtained by visually placing a continuum on both sides of the line and then integrating all over this range. Errors were estimated by moving the continuum upwards by half the value of the noise near the line position and re-computing the intensity and equivalent width.

Where possible the following nebular emission lines were measured: λ3727, the H Balmer line series including to H9, , λ4959,5007, λ5201, λ5876, λ6300, λ6548,6584, λ6678, [S ii] $\lambda\lambda$6717,6731, λ7065, [Ar iii] λ7136, λ7325, and [S iii] $\lambda\lambda$9069,9532. If present, broad emission lines at $\lambda \sim$ 4680 Å (referred to subsequently as the (blue) WR bump), , and indicative of Wolf-Rayet (WR) stars were also measured. The spectra were also inspected for the presence of stellar absorption lines like the Ca ii triplet, the CH G band at $\sim$ 4300 Å, Mg lines at $\sim$ 5200 Å, or TiO bands.

The spectra were deredened using the Whitford et al. (1958) extinction law as parametrised by Izotov et al. (1994) assuming an underlying absorption of $W() = 2$ Å and an intrinsinc Balmer decrement ratio of $I()/I() = 2.86$.

All detailed results including finding charts, line measurements, and a detailed analysis of the nebular properties will be published in a forthcoming paper.

table*[htb] Statistics of WR regions tab$_{w}rcentertabularllll|llllllGalaxy\#bluebump\#\#cand.\ bluebumpcand.\ cand.$

Properties of the HII region sample s$_{p}ropsThepropertiesofourgalaxysampleasgivenbytheNEDdatabaseandtheadoptedd$

A total of 121 spectra were extracted from the 95 slitlets. Nebular emission lines were detected in 88 spectra; 85 correspond to extra-nuclear regions.

$les), and the$ R$_{23}$ methods of Zaritsky et al. (1994, squares), and Edmunds & Pagel (1984, stars). See comments in text. fig$_{o}h_{c}ompare$